Photographic Tracking of Elementary Particles

Sheets of emulsion can be stacked so that the tracks of particles can be recorded in three dimensions.

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In the development of nuclear physics, a decisive role has been played by two principal types of instruments for detecting charged particles and making manifest the tracks that they produce in passing through matter—the counters and the track recorders. It is with the second of these two types of devices that I am here concerned.

The original instrument of this kind was developed by my old teacher, C. T. R. Wilson. In the period from 1900 to 1910 he was able to show that the passage of a charged particle through a gas saturated with water vapor could be made manifest by suddenly expanding the gas immediately before, or immediately after, the passage of the particle. As a result of the expansion, the air tends to become supersaturated, and in suitable conditions the water vapor condenses as small droplets on the individual charged ions and electrons produced in the gas by the particles passing through it.

The great advantage of the Wilson expansion chamber was that it gave a detailed picture of the ionization due to individual particles; in favorable conditions each particle wrote, as it were, its own signature, and ambiguities in the interpretation of phenomena were thereby greatly reduced.

Before the successful development of the Wilson chamber, many features of the interactions between atomic nuclei, and of the processes involved in the ionization of a gas by different radiations, had been inferred from a wide range of experiments with other devices. But with the Wilson chamber these processes were made immediately apparent in all their richness and variety.

To a generation which remembered the tone of the science of 40 years earlier, when it had seemed to many of the most eminent scientists of the day that it was improbable that we should ever be able to penetrate into the structure of atoms—and to some of whom the very idea of atoms appeared as no more than a convenient fiction—the Wilson photographs were an almost magical revelation of a new world. Wilson's pictures of the ionization of a gas by x-rays and, somewhat later, Blackett's photographs of the collisions of alpha particles with nuclei, and the disintegrations that they produced, gave a final demonstration of incomparable clarity that carried overwhelming conviction.

Fully Automatic Chamber

To obtain Wilson photographs of rare events, it was necessary, in some experiments, to make operation of the chamber automatic. Thus, the cross section for the collision of alpha particles with atomic nuclei is so small that there is a probability of only a few parts in a million that such a particle in passing through a gas will make a collision before reaching the end of its range. To demonstrate the disintegration of nitrogen by alpha particles, Blackett and his colleagues developed the fully automatic Wilson chamber, whereby the arduous experiments involved in photographing the tracks in the necessary numbers could be successfully undertaken. Later, Blackett and Occhialini developed the counter-controlled Wilson chamber, whereby charged particles due to cosmic radiation, in passing through Geiger counters disposed above and below the chamber, triggered its expansion; the passage of the particle was thus made to produce its own photograph.

Although in work with the great accelerators the Wilson chamber has now been replaced by bubble chambers, largely because they can operate with liquid hydrogen, many of the basic mechanical features developed in the automatic and counter-controlled Wilson chamber are embodied in the operation of the new instruments. And the power of the Wilson chamber to resolve the finest details of the ionization process has never been equalled in other instruments.

Use of Emulsions

The Wilson expansion chamber has the disadvantage that it is able to record tracks—under the conditions commonly employed—for only about 1/50 second. Since the resetting of the chamber takes about 1 minute, the fraction of the operating time usefully employed is very small. This feature of the Wilson chamber led to a consideration of the possibility of using photographic emulsions for recording tracks directly, since they would have the advantage of being continuously sensitive for long periods. An emulsion consists of myriads of microcrystals of silver halide embedded in gelatine. It was thought that the passage of a charged particle would cause some of those microcrystals penetrated to become developable, so that under the microscope the track in the processed emulsion would appear as a chain of black grains of developed silver, like black beads on an invisible thread.

The early experiments, including those of Walmsley and Makower, and of Kinoshita working in Rutherford's laboratory in Manchester, in the period 1909 to 1914, showed that it was indeed possible to record the tracks of alpha particles in some of the photographic emulsions commercially available at the time. The numbers of grains in the tracks were, however, small, and the tracks were therefore extremely tenuous.

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Early Disadvantages

In the early emulsions, the volume occupied by the silver halide crystals was only about one-eighth that of the surrounding gelatine in which they were embedded. As a result, the individual grains in the track of an alpha particle were widely separated, and the true beginning and end of a track were correspondingly uncertain. Further, the tracks of electrons and other weakly ionizing particles could not be distinguished in the available emulsions, so that the recorded phenomena compared unfavorably with the effects produced by similar processes in a Wilson chamber. And finally, the thickness of the emulsion commonly available was less than 1/20 millimeter, so that fast particles originating in the emulsion frequently escaped from it before reaching the end of their range. Their tracks were therefore incomplete.

As a result of the deficiencies of the early emulsions, the method was little regarded for more than 20 years. In the early 1930's, however, Blau and Wambacker returned to a consideration of the use of emulsions and showed that the tracks of protons as well as of alpha particles could be recorded in some commercial emulsions. They made experiments with protons recoiling from impact by fast neutrons, and with protons emitted from nuclear disintegrations produced by fast alpha particles from radioactive substances. In these experiments, also, however, the difficulty was that the apparent length of the observed tracks gave an imprecise measure of the true range of a particle and, therefore, of its initial energy. Later, Blau and her colleagues showed that it was possible to record also the tracks due to disintegrations produced at mountain altitudes by particles of the cosmic radiation.

Early Experiments in Bristol

My colleagues and I in Bristol became interested in the method during 1938. We had constructed a Cockcroft generator that gave protons of energy about 700 kev, and we had proposed to make experiments with the fast homogeneous groups of neutrons which are generated by the impact of fast protons on light elements such as lithium, beryllium, and boron. The original intention was to use a Wilson chamber to detect the "knock-on" protons projected by the neutrons, but W. Heitler, who was then working in Bristol, directed our attention to Blau's studies of cosmic radiation with photographic plates. We then made an experiment on the Jungfraujoch with a number of plates exposed under different thicknesses of lead, in an attempt to measure the rate of absorption of that component of the cosmic radiation which gave rise to the observed "stars," as the nuclear disintegrations were called.

These experiments on cosmic radiation made us familiar with the elementary features of the photographic method, and we decided to use it in place of a Wilson chamber to try to detect the protons projected by fast neutrons. Using Ilford "half-tone" plates, we found that after about an hour's exposure of a plate with a superficial area of 2 square centimeters, the emulsion being one 30th of a millimeter thick, we were able, after developing the plate, to measure under the microscope hundreds of tracks due to proton recoil in the course of a few hours. The energy spectrum of the neutrons, thus determined in a day or two, was superior in precision to that obtained in the course of about six months' work in experiments with the Wilson chamber. It was evident that for such experiments the photographic method had a number of important advantages.

At the time of these experiments, we were very poorly acquainted with the literature on the subject. In a sense I think this was an advantage, for had we known of all the early unsuccessful experiments to determine the "energy spectra" of charged particles, we might have been discouraged from making a new attempt. In fact, we were fortunate, for the early emulsions, produced for quite different purposes, were not uniform in their performance in recording tracks, and the importance of fading of the latent image and of proper conditions of storage were not appreciated at the time. By chance, the first plates we employed were of relatively high sensitivity. A second circumstance from which we benefited was that, unlike the earlier workers who had employed relatively weak radioactive sources to produce the disintegrations, we had homogeneous beams of relatively great intensity, and we were thus able to demonstrate conclusively some of the most important advantages of the method.

Technical Innovation

By 1945, when World War II ended, a modest field of study in nuclear physics for the photographic emulsion had been established, but it was still limited by the poor quality of the tracks. Attempts had been made to increase the sensitivity of the emulsion and the proportion of silver bromide to gelatine within it, but with little success. But, in 1945, through a technical innovation in manufacturing methods, Dodd and Waller of Ilford Ltd., London, were able to produce emulsions in which the proportion of halide to gelatine was increased over the usual values approximately eightfold, and at about the same time Demers, in Canada, achieved a similar result in his own laboratory.

The advantages of the concentrated emulsions were immediately apparent. The tracks of alpha particles from radioactive substances took the form of almost solid rods of developed grains, and even with less strongly ionizing particles, like fast protons, the tracks were clearly apparent. These developments improved the standing of the photographic method and the precision of the measurements which could be made with it, but it was not until new experiments with cosmic radiation were made that the full potentialities of the method were realized.

In 1945, in collaboration with Occhialini, who had just returned to Bristol from Brazil, we made exposures of the new emulsions at the Pic du Midi in the Pyrenees, and Perkins at the Imperial College, London, made similar experiments on the Jungfraujoch. When the plates were developed and examined under the microscope, it was immediately apparent that a new range of phenomena had been made manifest.

Disintegration of Nuclei

One of the earliest discoveries, made independently by Perkins and by us in Bristol, was that of the disintegration of nuclei by particles after they had reached the end of their range in emulsion. The mass of these particles could be estimated from the characteristics of their tracks and was found to be between 200 and 300 times that of the electron. They were at first thought to be negative mu mesons, discovered in the period 1936 to 1938 by Anderson and Neddermeyer, but almost immediately afterwards examples were found in Bristol of the so-called pi-mu decay.

It was soon shown that a new elementary particle, the pi meson, had been discovered, which could exist in either positively or negatively charged form. The positive particles, when they are brought to rest in matter, cannot approach nuclei because of the repulsion between positive particles. They remain free and decay with a mean lifetime of about 2.6×10^{-8} second. On the other hand, the negative particles are attracted to nuclei, with which they interact, the energy corresponding to their rest-mass being supplied to produce the disintegration of the capturing nucleus.

The discovery of the pi meson illustrated a number of features of the photographic method which were of central importance for its application in the discoveries of new types of elementary particles in the ten years that followed. First, the continuous sensitivity of the emulsion permits rare phenomena to be recorded in exposures of long duration. Second, the observation of the phenomena is so close and intimate that a single example of a new process has frequently permitted correct assessment of its significance, and a few examples have commonly provided decisive evidence. Third, the emulsion is a solid with a density approximately 2000 times greater than that of a gas at normal pressure and temperature. As a consequence, a particle with a given energy is brought to rest in an emulsion after a length of path, and in a period of time, about 2000 times shorter than in a Wilson chamber. It follows that particles with mean lifetimes in the interval from 10^{-8} to 10^{-10} second, when created in nuclear disintegrations in an emulsion, are commonly arrested in it before decaying, whereas in a gas they almost invariably decay while still in motion.

There are important advantages in studying the decay of particles at rest, for the vector sum of the momenta of the secondary particles must then be zero. On the other hand, when, as in a gas, particles decay in flight, it is necessary to know the momentum of a primary particle at the instant of its decay if the principle of the conservation of momentum is to be applied to the analysis of the transformation.

In the ten years that followed the discovery of the pi meson, the photographic method was widely applied both in studies of nuclear disintegrations produced by particles of the cosmic radiation and in investigations with the intense controlled beams of particles produced by the great accelerators as they came into operation.

The method was found to be particularly appropriate for studying cosmic rays with balloons, for it is only necessary to support the emulsions at great altitude for a given period and subsequently to recover the material for development and examination under the microscope. There is, therefore, a complete absence of any complications associated with the use of auxiliary apparatus. And for such work, the continuous sensitivity is a decisive advantage. The most important discoveries about elementary particles made with the photographic method in the period from 1947 to 1959 are included in Table 1.

Many of the discoveries referred to in Table 1 were greatly assisted by two important technical advances—first, by the production of more sensitive emulsions, which were able to give a clear track for even the most weakly ionizing particles known to us, such as fast electrons, and second, by the production of emulsions much thicker than those of conventional photographic plates, and without glass support.

Table 1. Instruments used in the discovery of various elementary particles.

Particle	Source of radiation	Specific behavior or measurement	Instrument used for detection
e^-	Discharge tube	Ratio e/m	Fluorescent screen
e^+	Cosmic rays	Ratio e/m	Wilson cloud chamber
μ^+ μ^-	Cosmic rays	Absence of radiation loss in passage through Pb (also decay at rest)	Wilson cloud chamber
π^+	Cosmic rays	π-μ decay at rest	Nuclear emulsion
π^-	Cosmic rays	Nuclear interaction at rest	Nuclear emulsion
π^0	Accelerator	Decay into γ rays	Counters
K^+	Cosmic rays	$K_{\pi 3}$ decay	Nuclear emulsion
K^-	Cosmic rays	Nuclear interaction at rest	Nuclear emulsion
K^0	Cosmic rays	Decay into $\pi^+ + \pi^-$ in flight	Wilson cloud chamber
n	Polonium plus beryllium	Mass determination from elastic collisions	Ionization chamber
$\bar{p}$	Accelerator	Measurement of e/m plus detection of annihilation	Counters
$\bar{n}$	Accelerator	Detection of annihilation	Counters
Λ^0	Cosmic rays	Decay in flight into $p^+ + \pi^-$	Wilson cloud chamber
$\bar{\Lambda}^0$	Accelerator	Decay in flight into $\bar{p} + \pi^+$	Nuclear emulsion
Σ^+	Cosmic rays	Decay at rest	Nuclear emulsion
Σ^-	Accelerator	Decay in flight into $\pi^- + n^0$	Diffusion chamber
Σ^0	Accelerator	Decay in flight into $\Lambda^0 + \gamma$	Bubble chamber
Ξ	Cosmic rays	Decay in flight into $\pi^- + \Lambda^0$	Wilson cloud chamber
Ξ^0	Accelerators	Decay in flight into $\pi^0 + \Lambda^0$	Bubble chamber

International Collaboration

By assembling many sheets of emulsion, it was possible to build up a large sensitive volume for recording tracks. Whereas, in the early days, only a single layer of emulsion had been available, so that only a small fraction of the charged particles originating in disintegrations within it were observed to reach the end of their range, in the new conditions the tracks could be traced from one emulsion to the next throughout a large stack. The field of application of the method was thereby greatly increased; particles of much greater energy could be followed to the end of their range, and their nature and kinetic energy could be determined. Whereas the early experiments on cosmic rays in 1947 had been made with emulsions with a total volume about 0.1 cubic centimeter, already by 1955 stacks made up of several hundred sheets 0.6 millimeter thick, and with a total volume of 7 liters, were widely employed.

It is these developments that provided the necessary background and experience for the extensive international collaborations in the study of nuclear collisions at extremely high energies which are now being carried out. These operations involve exposing balloon-borne stacks 80 liters in volume to the cosmic radiation at altitudes above 100,000 feet for periods of about 20 hours.